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COMPARISON OF CHUTE AND STILLING BASIN PERFORMANCE FOR THREE DIFFERENT DROP BOX INLETS

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COMPARISON OF CHUTE AND STILLING BASIN PERFORMANCE FOR THREE DIFFERENT DROP BOX INLETS

By W. O. Ree[1]

ABSTRACT

Three different drop (entrance box) inlets were tested and compared to determine their influence on the performance of a chute spillway and a stilling basin at the outlet of the chute. Test results indicated that the steep and level entrance boxes did not affect the performance of the spillway and stilling basin differently than did the deep (original design) entrance box. Upstream pool levels, wave heights along the chute walls, and scour depths in the downstream channel were alike for the three entrance boxes. An advantage of the steep entrance box was a smaller associated uplift force.

INTRODUCTION

Three different drop (entrance box) inlets were tested and compared for their influence on the flow in a chute spillway and on the performance of a Saint Anthony Falls (SAF) stilling basin at the outlet of the chute. The tests were undertaken to determine if the entrance to a chute spillway need be a deep entrance box or if a shallow box would do as well. The deep entrance box was selected by the designers of a chute spillway for Boomer Lake at Stillwater, Okla., because it was a standard design of proven performance (fig. 1). However, they were concerned about the uplift force on the box. This force could be about 40,000,000 lb for the 100-by 200- by 26-ft box (with some allowance made for slab thicknesses), so the designers asked the Water Conservation Structures Laboratory for suggestions for alternate designs which would not have so large an uplift force.

The first suggestion was a much shallower (steep) box with a floor sloping from a small depth at the upstream end to a larger depth at the chute entrance (fig. 1). This type of box was first tested in 1934 by L. H. Kessler.[2] In his report, Kessler stated, ". . . a shallow pit section will discharge almost as much water as will be discharged by the deep pit. The use of the shallow pit will obviously reduce uplift forces." It was this potential for reduced uplift force that made the steep-box design so attractive. However, there was concern over using a design 40 years old, since the deep box now in use is the result of experience since that time. According to the designers, the advantage of the deep box is the dissipation of rollers that form under the side-weir nappes. If the roller were not dissipated, it would persist in the flow along the wall and possibly interfere with the operation of the stilling basin at the outlet. So it is possible that any savings resulting from the use of a steep entrance box could be offset by the added cost of the stilling basin required to cope with a disturbed flow. Since the cost advantage could have favored either the steep box or deep box and since the savings potential for the structure involved was great, model experiments to resolve the issue were justified. Because results of such model

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[2] Kessler, L. H. 1934. Experimental investigation of the hydraulics of drop inlets and spillways for erosion control structures. Univ. Wis. Bull., Eng. Exp. Stn. Ser. No. 80, 66 pp.

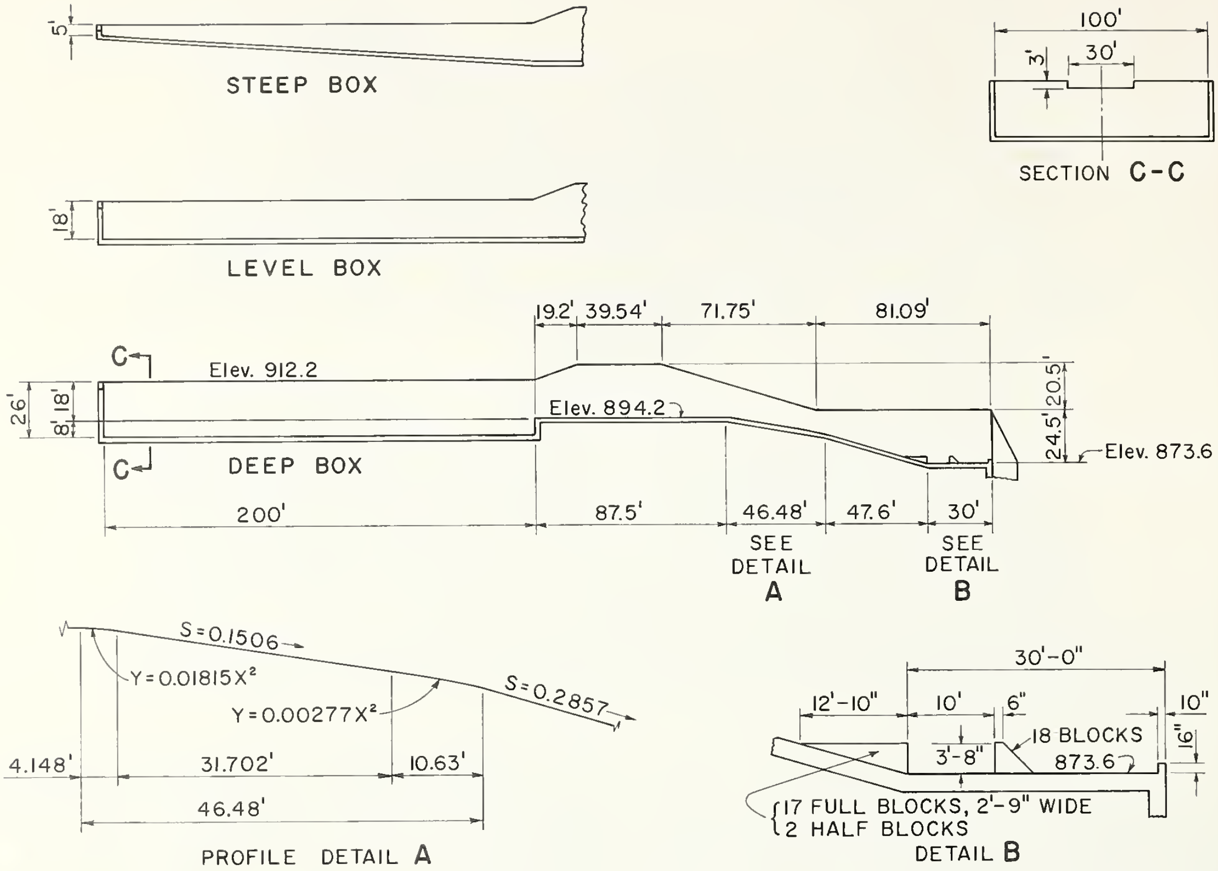

FIGURE 1.—Chute spillway design for Boomer Lake with the three entrance boxes used in the model tests.

studies could be applied to other, similar structures, it was decided to conduct the experiments. The tests also included a level box, an entrance form intermediate between the deep and steep boxes (fig. 1).

The performances of steep and level entrance boxes were compared with the performance of the deep entrance box. Performance observations included the effect on upstream pool level, the wave patterns in the chute as they affected maximum flow depths along the chute walls, and the scour patterns and scour depths in an erodible bed around and downstream of the stilling basin.

The model tests were limited to comparisons and indications of the quality of performance of the chute and stilling basin for each of the three entrance boxes. The tests were not intended to nor did they provide complete design guidance. For example, the sizing and placing of riprap, which might be needed at the outlet, were not investigated. Also, the model did not simulate the prototype channel downstream from the spillway. Instead, a simple, trapezoidal section of straight alinement was used. Descriptions of the prototype, the models, and the results of the tests are presented in this report.

PROTOTYPE

The chute spillway is for Boomer Lake at Stillwater, Okla. This lake was created by the construction of a dam in 1926 and for the next 25 years was the water supply for the city. Presently, the lake serves as a cooling pond for the condensers of turbines for electric-energy generating stations and also as a recreational facility. The lake provides some flood control for the city, so it is being considered for incorporation into the flood control plan (Public Law 566) for Stillwater Creek, to which Boomer Creek is tributary. If the lake is to be a part of the plan, a new spillway will be required for the lake to meet present-day standards for capacity and stability.

The capacity of the spillway must be large enough to convey the flood resulting from probable maximum precipitation. This flood was estimated by the Soil Conservation Service to be 24,300 ft^3/s. The standard project flood of the U.S. Army Corps of Engineers for this site is 9,700 ft^3/s, a rate approximately equivalent to a 500-year flood.

Water-surface elevations in the channel (immediately downstream from the spillway) for various discharges were estimated from water-surface profiles calculated by the Corps of Engineers. The estimated relationship between the water-surface elevation and discharge rate is shown in figure 2.

The entrance to the spillway will be in the lake, so approach velocities will be low. Figure 3 shows the location of the proposed new spillway with respect to the dam and the present spillway.

The lake is in an urban area, and residences on the west shore set the maximum permissible water-surface elevation. The minimum water-surface elevation was established by the need for a lake of sufficient size to provide cooling water for the electric-energy generating stations. These constraints were met by the designers of the new spillway and were not a matter of concern in this study; they are mentioned only to show that the options available to the designers were quite limited.

The site conditions and constraints indicated the need for a spillway with a long weir and a chute to convey the flow through and over the dam. A very large entrance box was required to provide the needed weir length. The chute profile (with its two slopes) fit the site, and the vertical curves connecting the floor slopes avoided separation of flow from the chute surface at their intersections. Energy dissipation and scour control were provided by a SAF still-

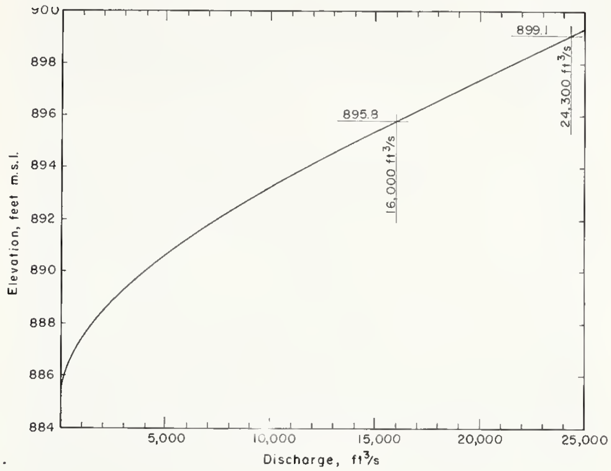

FIGURE 2.—Relationship between discharge rate and water-surface elevation in channel immediately downstream from stilling basin.

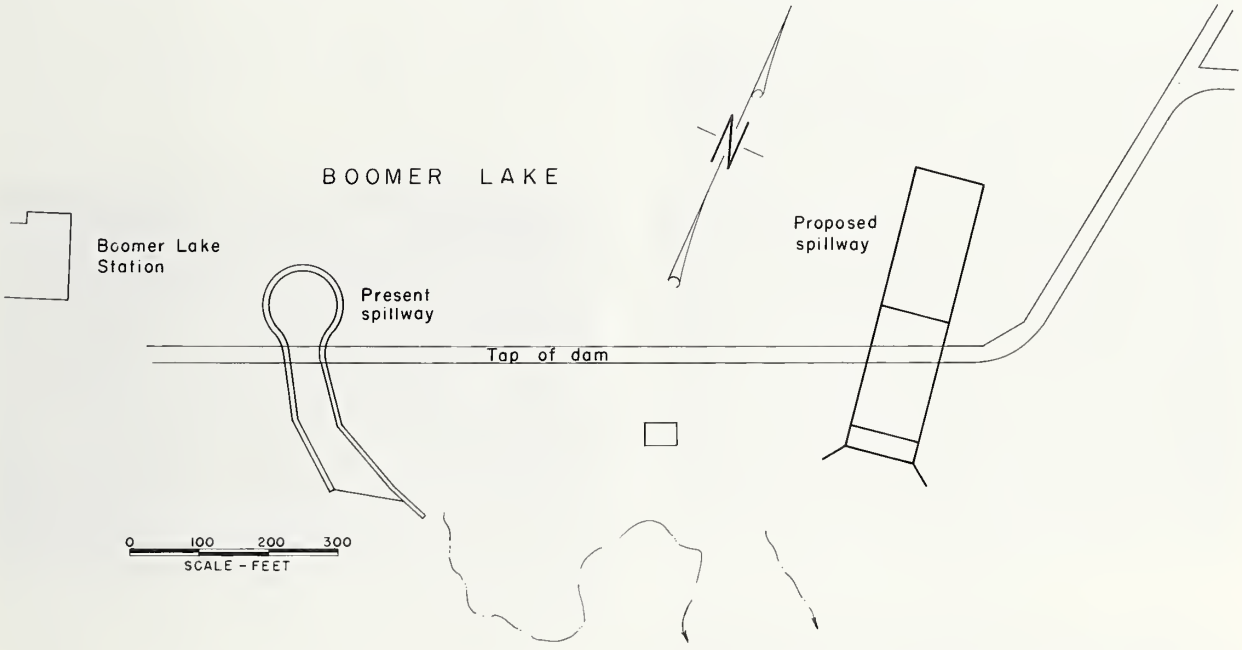

FIGURE 3.—A portion of Boomer Lake showing dam and present and proposed spillways.

ing basin[3] at the outlet. The stilling basin was designed for a flow of 16,000 ft^3/s rather than for the full flow of 24,300 ft^3/s because a larger flood was extremely unlikely.

SCALE MODEL

A model basin 10 ft wide, 40 ft long, and 2.5 ft deep (supplied by a 12-inch pipeline directly from a large 3,400-acre lake) was available for these studies. The capacity of the supply line was about 5 ft^3/s. A scale of 1 to 50 was selected for the model chute spillway. This scale provided an equivalent prototype width of 500 ft for the downstream channel, which was deemed adequate for scour studies. Also, the required maximum discharge was well within the capacity of the system. The scale ratios were length, 50:1; velocity, 7.07:1; time, 7.07:1; and discharge, 17,678:1.

The model of the original design was built of redwood and was given three coats of spar varnish. An aluminum plate was inserted in the drop-inlet box to simulate the level and steep boxes. This plate, when in place, rested on simple supports and was sealed with calking material at its juncture with the chute. A steel frame on the concrete floor of the basin supported the model. Adjustments were provided in the frame to permit careful leveling of the model. After the model was installed, the basin was filled with masonry sand, which was struck off to cross-section and grade with traveling screeds. The sand placed in the area downstream from the stilling basin was sieved through a 16-mesh screen. Figure 4 shows the installation of the model in the basin.

Because of the lake's large size, its water level was unaffected by the water withdrawal for the tests, and test flows remained steady. Flow control was by valve in the 12-inch line, with fine adjustment by a 2-inch line and valve in parallel with the 12-inch line. Flows were measured with a 6-inch orifice plate, which had been calibrated in place. Pressure drop across the orifice was measured with a U-tube differential manometer, with water as the fluid. Accuracy of the discharge measurement was probably within ±2 percent.

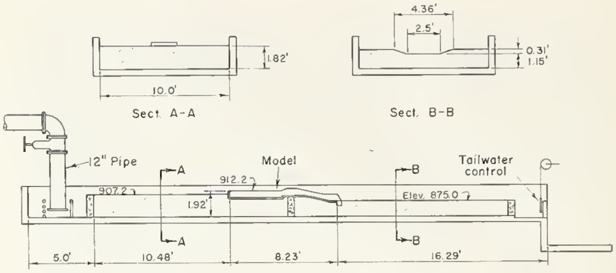

FIGURE 4.—Model chute spillway as installed in basin at laboratory.

MODEL TESTS

Tests were run on each of the three entrance forms for flows of 16,000 ft^3/s and 24,000 ft^3/s, a total of six tests. Before each test the downstream channel was shaped to a standard trapezoidal cross section and a level grade. Figure 5 shows the downstream channel before testing.

Before admitting the test flow, the downstream channel was slowly filled to the desired tailwater level from an auxiliary supply line. The test flow was then turned on and brought to the full rate as quickly as possible, and the tailwater control gate was simultaneously lowered to maintain the predetermined tailwater level. The test flow was allowed to run for 2 hours 47 minutes and was then abruptly stopped. The tailwater gate was raised slowly to prevent too rapid a drainoff of the downstream channel, which could have caused additional erosion. This maneuver was done to preserve the scour pattern caused by the test flow. The testing period of 2 hours 47 minutes was required to obtain the required observations during the first test, and

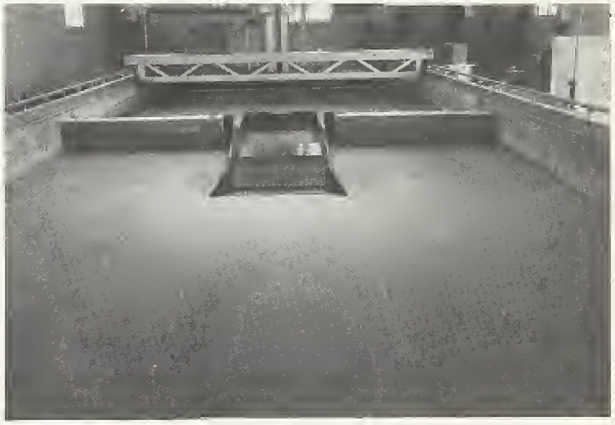

FIGURE 5.—Model chute spillway in basin before tests. (White-wool yarn lines in foreground define top and bottom edges of channel.)

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[3] Blaisdell, F. W. 1959. The SAF stilling basin. U.S. Dep. Agric., Agric. Handb. No. 156, 16 pp.

all subsequent tests were held to this duration. In prototype terms the test duration was nearly 20 hours. A view of the model basin during the test at 24,000 ft^3/s with the steep entrance box is shown in figure 6.

During the test flow, point-gage measurements were made to determine water-surface elevations in the head pool and at selected points in the chute, stilling basin, and downstream channel. In the chute, 10 rapidly repeated point-gage measurements were made at 10 equally spaced points across the chute, with the first point being located one-twentieth of the chute width from the wall, or 2.5 ft in the prototype. These lines of points were spaced at intervals along the chute equivalent to 20 ft in the prototype, starting at the chute entrance and ending just above the jump.

After the test flow the centerline profile of the downstream channel and a cross section at the station of deepest scour were measured. White wool yarn was then placed on the contours at 5-ft vertical intervals in the scoured area downstream from the stilling basin, and a photograph was made from directly overhead.

RESULTS

Views of the test flows are shown in figures 7 and 8. There were minor differences in the outward appearance of the water surfaces at the upper end of the chute for the three entrances for the flows of 16,000 ft^3/s and 24,000 ft^3/s. However, immediately upstream from the jump the water surfaces were alike for all three entrances.

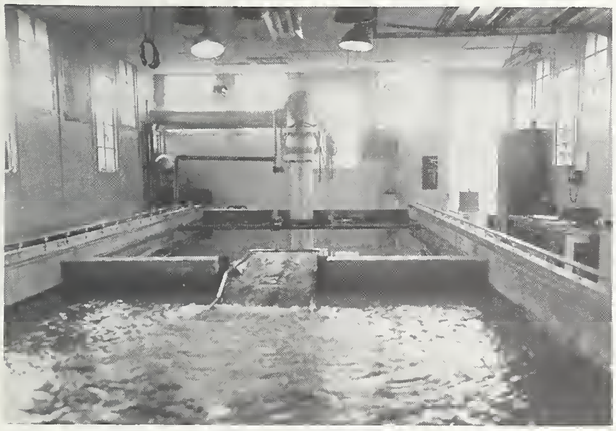

FIGURE 6.—Model chute spillway being tested at 24,000 ft^3/s with the steep entrance box. (Rails on basin walls support cross-sectioning apparatus.)

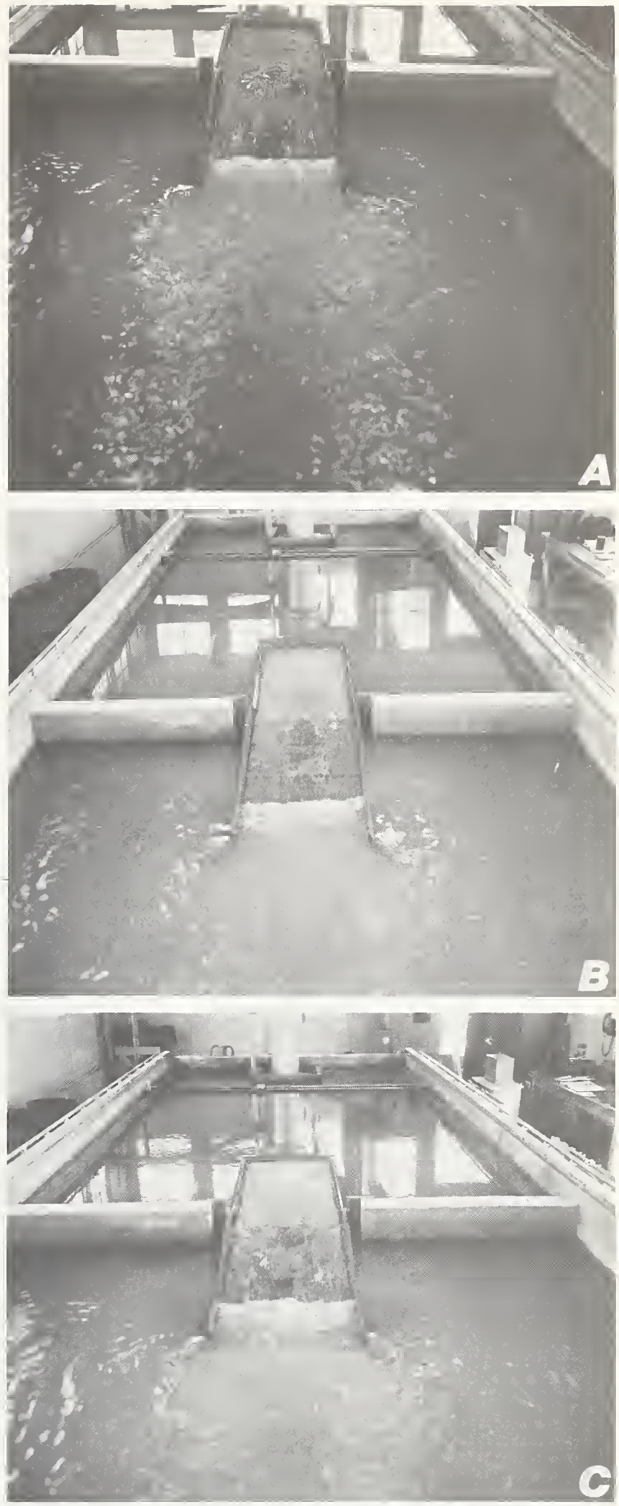

FIGURE 7.—Model chute spillway being tested at 16,000 ft^3/s with each of the three entrance boxes. *A*, Deep box. *B*, Level box. *C*, Steep box.

Head Over Weir

The heads over the weir for the three entrance boxes for a flow of 24,000 ft^3/s are shown in figure 9. The C value in each tabulation in figure 9 is the weir coefficient for the formula $Q=CLh_H^{3/2}$, where Q=discharge (cubic feet per second), L=weir length (feet), and h_H=head on weir (feet). The water-surface elevation at the upstream end of a box inlet increases as the box becomes shallower but not sufficiently so as to increase the headwater level. There was no difference in headwater elevations for the three box inlets.

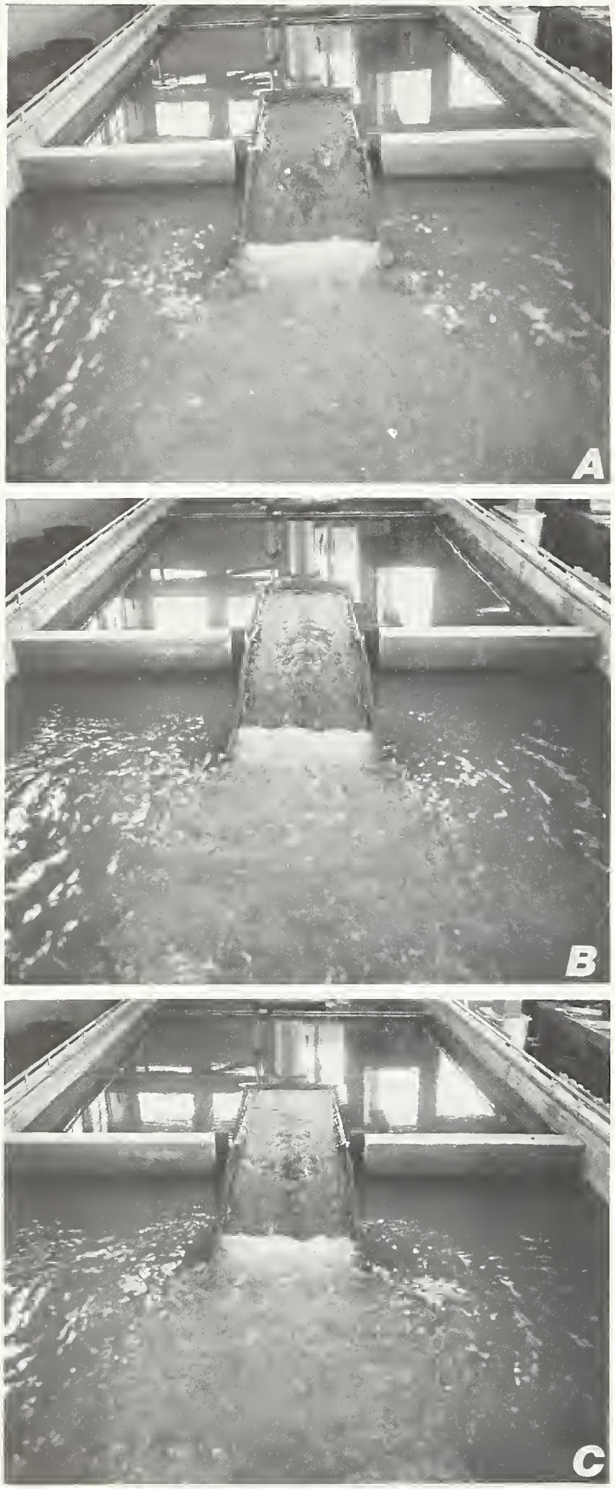

FIGURE 8.—Model chute spillway being tested at 24,000 ft³/s with each of the three entrance boxes. *A*, Deep box. *B*, Level box. *C*, Steep box.

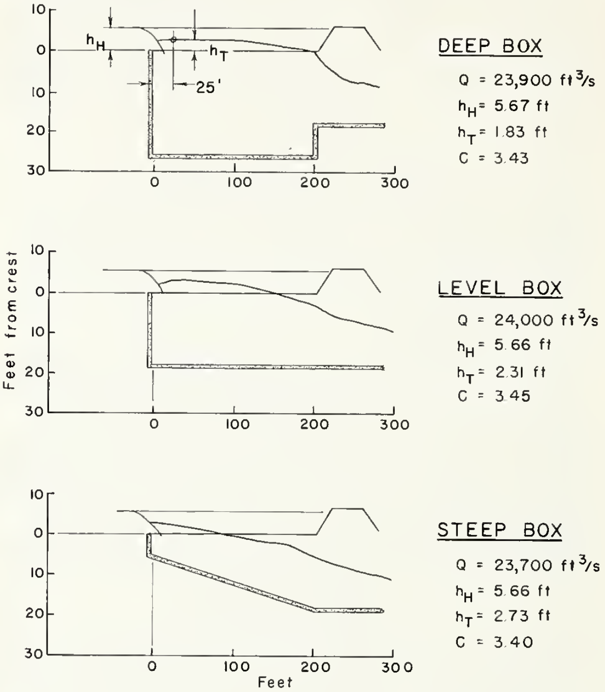

FIGURE 9.—Average water-surface profiles at 24,000 ft³/s for the three entrance boxes.

Water-Surface Roughness in Chute

A measure of the roughness of the water surface in the chute was obtained by calculating the standard deviation of the water-surface elevations in the chute. The 100 measurements of water-surface elevation (made at each measured section) provided the values of the standard deviation for a flow of 24,000 ft³/s (table 1). The average water surface was smoothest in the chute with the deep entrance box and was roughest in the chute with the steep entrance box. However, the difference between the two in degree of water-surface roughness was small, 0.21 ft.

Depths Along Chute Walls

In figure 10 the profile of maximum water-surface elevation along the chute walls for the steep entrance box can be compared with the

TABLE 1.—*Standard deviation of water-surface elevations in the chute for a flow of 24,000 ft^3/s*

Distance from chute entrance[1] (ft)	Entrance box		
	Deep (ft)	Level (ft)	Steep (ft)
0	0.88	0.96	0.76
20	1.24	1.12	2.30
40	.54	1.02	1.14
60	.75	.94	.94
80	.46	.49	.65
100	.36	.26	.26
120	.42	.57	.49
140	.42	.50	.54
160	.31	.26	.25
Average	.60	.68	.81

[1] All dimensions are prototype.

profile for the chute with the deep box for a flow of 24,000 ft^3/s. A similar comparison can be made in figure 11 for the chute with the level entrance box. In plotting these profiles the maximum level of the fluctuating water surface was used. There was no real difference between the profiles in the lower reaches of the chute.

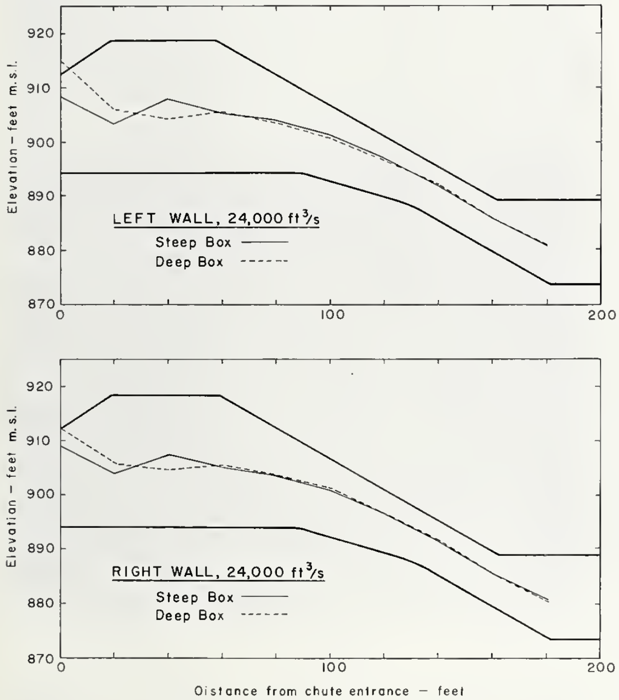

FIGURE 10.—Maximum water-surface elevations along chute walls at 24,000 ft^3/s for the steep and deep entrance boxes.

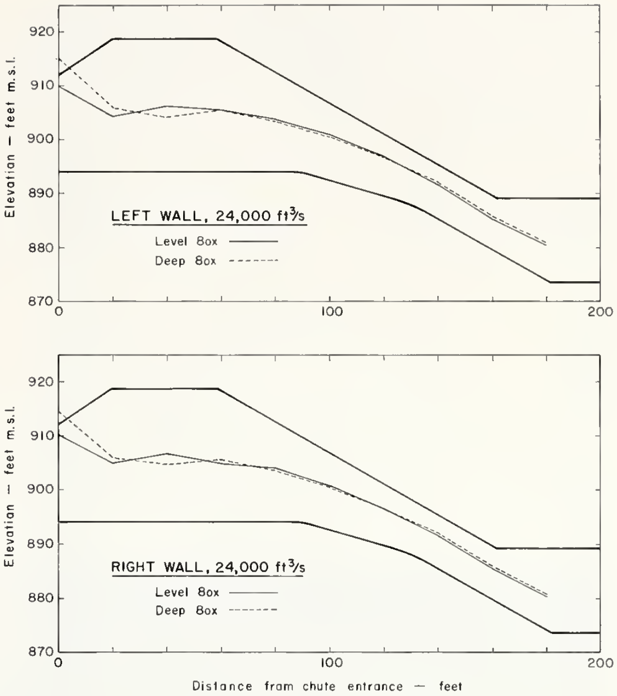

FIGURE 11.—Maximum water-surface elevations along chute walls at 24,000 ft^3/s for the level and deep entrance boxes.

Froude Numbers, Basin Lengths, and Flow and Tailwater Depths

The Froude numbers of the jet entering the stilling basin were calculated for the test flows of 16,000 ft^3/s from the formula used by Blaisdell (cited in footnote 3), namely, $F=V^2/gd$, where F=Froude number, V=flow velocity (feet per second), g=acceleration of gravity (feet per second squared), and d=flow depth (feet). Required stilling-basin dimensions (based on the same Froude numbers) were calculated from the formulas given by Blaisdell and compared with the dimensions provided (table 2).

The Froude number of the flow entering the stilling basin increased as the entrance box was changed from deep to level to steep. This increase was attributed to a higher energy content of the flow for the shallower entrance boxes. The flow for the steep box sped down the ramp rather than plunging into a deep pool, and less energy was dissipated in the entrance box.

The depth of flow in the chute of the model was greater for all tests than the 3.68 ft predicted by the designers. In trying to find the reason for this, it was necessary to calculate the friction

TABLE 2.—*Flow depths and Froude numbers in the chute and calculated and available tailwater depths and basin lengths for the tests at 16,000 ft^3/s*[1]

Entrance box	d_1 (ft)	F	Calculated		Available (design)	
			d_2' (ft)	L_B (ft)	d_2' (ft)	L_B (ft)
Deep	4.92	6.67	16.2	34.3	21.9	30
Level	4.85	7.00	16.3	34.1	21.9	30
Steep	4.66	7.88	16.5	33.5	21.9	30
Design	3.68	16.40	18.1	30.0	21.9	30

[1] d_1 is depth, normal to chute, of jet entering stilling basin. F is Froude number of flow. d_2' is required tailwater depth above stilling basin floor. L_B is stilling basin length.

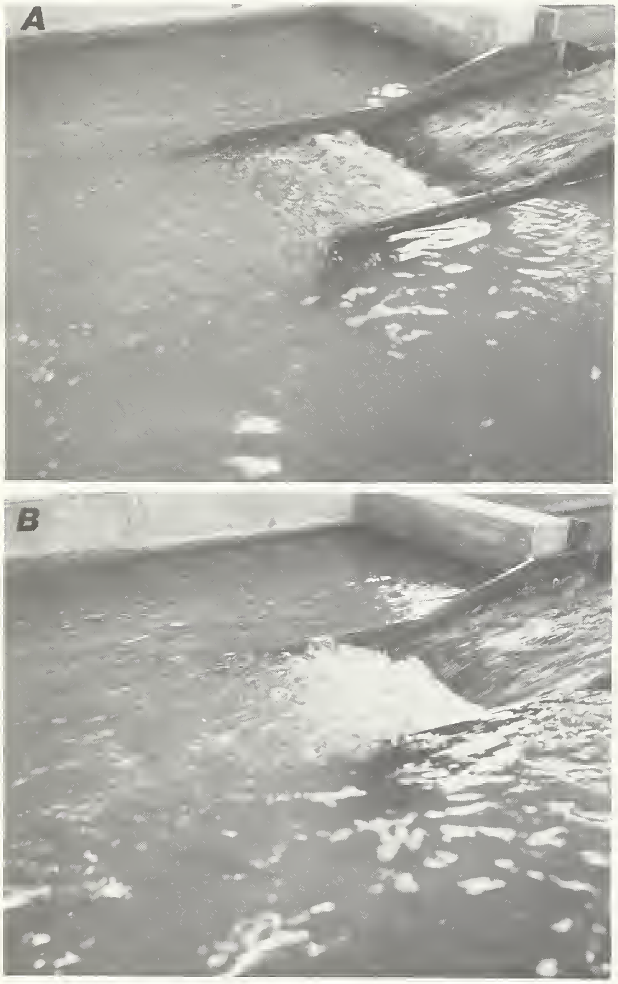

FIGURE 12.—Stilling basin performance for flows of 16,000 ft^3/s and 24,000 ft^3/s. *A*, Design flow of 16,000 ft^3/s—basin performance was very satisfactory. *B*, Flow of 24,000 ft^3/s—flow overloaded basin but performance was fairly satisfactory.

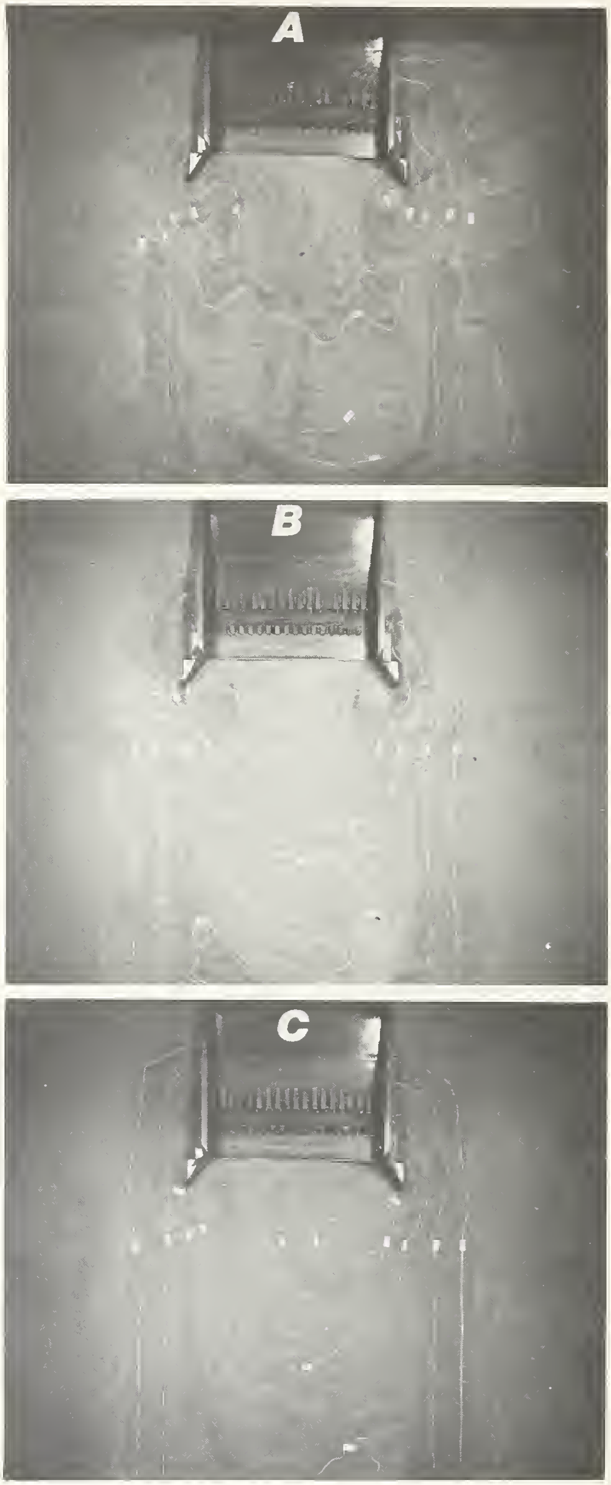

FIGURE 13.—Overhead views of channel downstream from spillway after a flow of 16,000 ft^3/s for 20 hours for the three entrance boxes. *A*, Deep entrance box. *B*, Level entrance box. *C*, Steep entrance box.

loss in the model. However, with the small depths involved, the precision of the depth determination in this small scale model was not sufficient. Some of the depth measurements indicated a gain in energy down the slope, which is impossible. So this approach was abandoned, and no further explanations for the depth differences were attempted.

The larger than predicted values of d_1 required smaller values of d'_2 and larger values of L_B than those provided in the original design. However, the stilling basin worked satisfactorily for a flow of 16,000 ft³/s. Evidently, some minor variation from the standard dimensions is tolerable in the SAF basin.

Stilling-Basin Performance

The difference between the stilling-basin performance for the flows of 16,000 ft³/s and 24,000 ft³/s can be seen by comparing figures 12*A* and 12*B*. For the design flow of 16,000 ft³/s most of the extreme turbulence associated with the hydraulic jump was confined to the area around the juncture of the chute and stilling basin. The outflow from the basin was of relatively "fine grained" turbulence, with uniform dispersion across the channel, whereas for the probable maximum flow of 24,000 ft³/s, extreme turbulence occurred over most of the stilling basin, and the flow overtopped the basin walls by about 1 ft. The outflow turbulence was "coarser grained" than that for the design flow and was not as uniformly dispersed across the downstream channel. Views from directly overhead of the vicinity of the stilling-basin outlet after a flow of 16,000 ft³/s for 20 hours are shown in figure 13. There was no real difference in the scour patterns for these three tests; the basin performed well in each instance. Centerline pro-

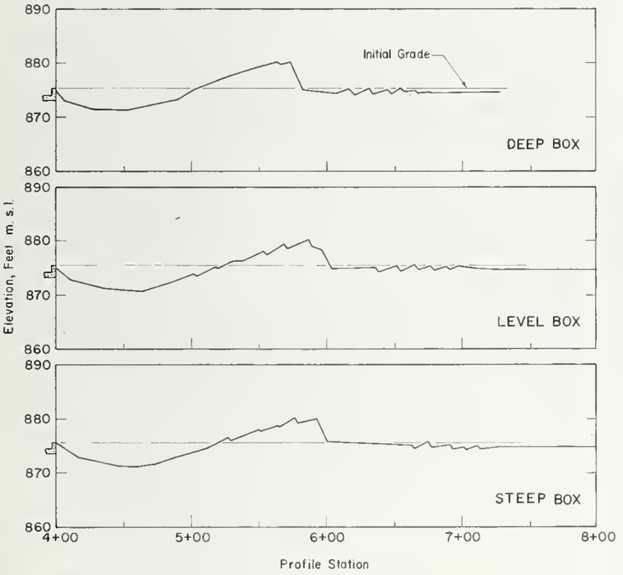

FIGURE 14.—Centerline profiles of channel downstream from spillway after a flow of 16,000 ft³/s for 20 hours for the three entrance boxes.

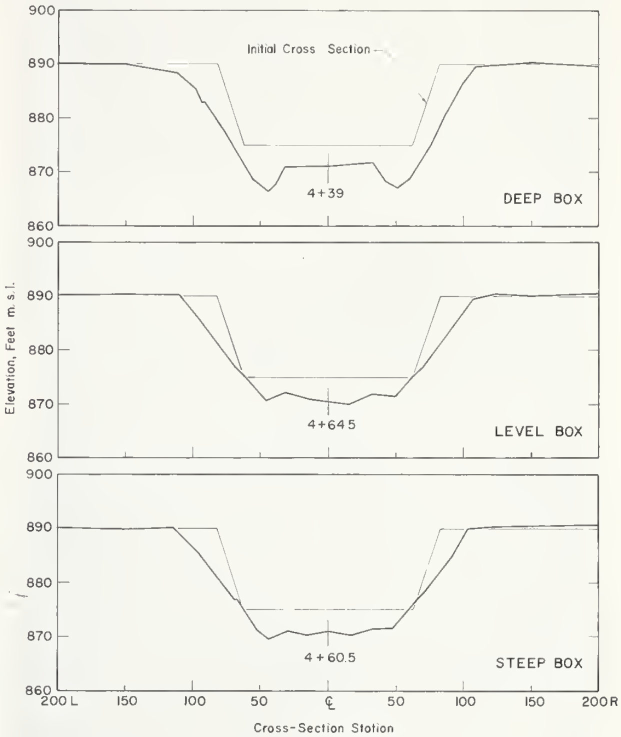

FIGURE 15.—Cross sections of channel downstream from spillway at point of deepest scour after a flow of 16,000 ft³/s for 20 hours for the three entrance boxes. (Number at cross-section centerline is the profile station.)

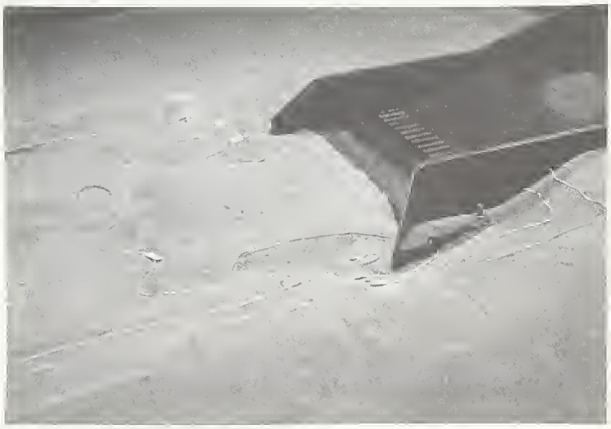

FIGURE 16.—Channel immediately downstream from spillway after a 20-hour flow at 16,000 ft³/s.

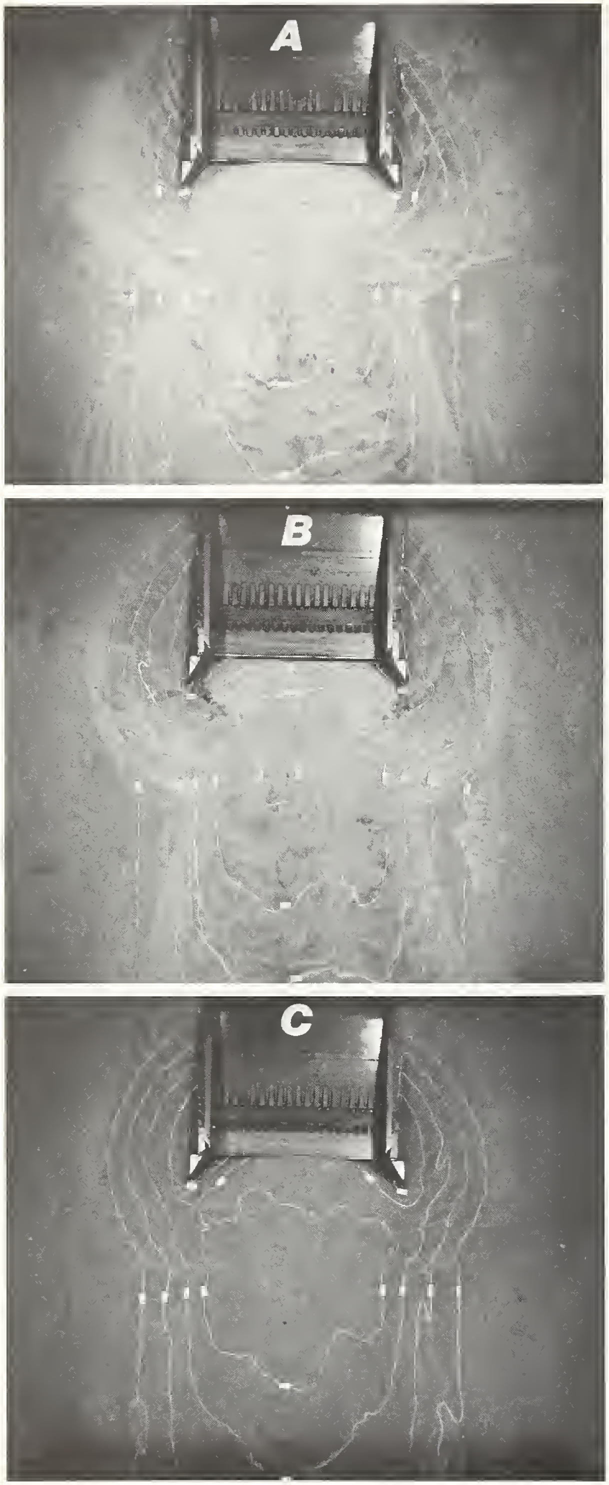

FIGURE 17.—Overhead views of channel downstream from spillway after a flow of 24,000 ft^3/s for 20 hours for the three entrance boxes. *A*, Deep entrance box. *B*, Level entrance box. *C*, Steep entrance box.

files of the channel downstream from the spillway for each of the three entrance boxes after a flow of 16,000 ft^3/s are shown in figure 14. Cross sections taken through the point of maximum scour depth in the channel downstream from the spillway are shown in figure 15. The profiles and cross sections show no major difference in the scour depths for the three test conditions. Scour immediately around the spillway outlet provided another measurement of the performance of the stilling basin for each of the three chute entrances. Figure 16 shows the scour around the left-wing wall of the stilling basin after the test with the deep entrance box. Maximum scour depths occurred at or near the ends of the wing walls (table 3). No particular trend was indicated by these wing-wall scour depths, and there was probably no real difference among them.

TABLE 3.—*Maximum scour depths around the stilling basin for the three entrance boxes*

Entrance box	Flow of 16,000 ft^3/s (ends of wing walls)		Flow of 24,000 ft^3/s (back of wing walls)	
	Right wall (ft)	Left wall (ft)	Right side (ft)	Left side (ft)
Deep	6.8	8.7	13.5	12.2
Level	6.5	9.1	13.4	12.4
Steep	8.5	5.0	13.0	12.5

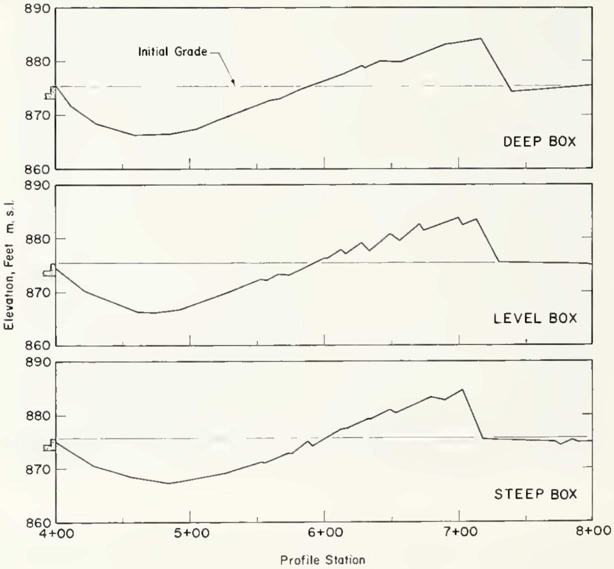

FIGURE 18.—Centerline profiles of channel downstream from spillway after a flow of 24,000 ft^3/s for 20 hours for the three entrance boxes.

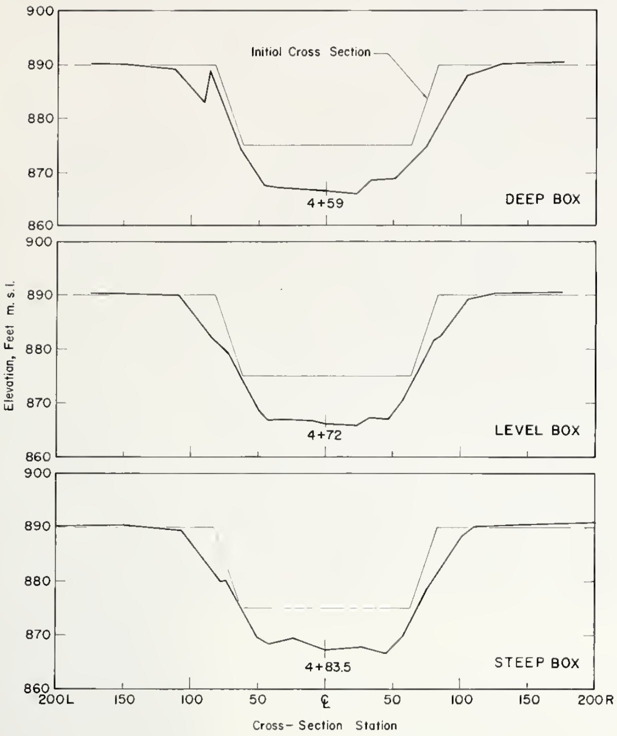

FIGURE 19.—Cross sections of channel downstream from spillway at point of deepest scour after a flow of 24,000 ft³/s for 20 hours for the three entrance boxes. (Number at cross-section centerline is the profile station.)

The scour patterns for the test flows of 24,000 ft³/s are shown in figure 17. They were similar for all three entrance conditions; no real difference was evident. Centerline profiles for the test flows of 24,000 ft³/s are shown in figure 18, and the cross sections at the point of maximum scour are given in figure 19. These plottings also indicate no difference in stilling-basin performance for the three entrance conditions. The deepest scour for these tests occurred to the left and right of the stilling basin, back of the wing wall. The depths for the three entrance conditions are given in table 3. There was no real difference in either the wing-wall scour depths or the maximum scour depths for the three entrance conditions.

The scour depths reported are those observed in the model transformed to prototype scale. They are not predictions of the scour depth to be expected in the prototype. The depths are relative only, but they do permit a comparison of the performance of the stilling basin under three different entrance conditions.

CONCLUSIONS

The type of entrance box used did not affect the performance of the chute spillway and stilling basin with respect to upstream pool level, maximum water surface elevations along the wall, or scour patterns and depths in the channel downstream from the stilling basin. Scour could be excessive around the wing-wall area for any of the three designs, which would possibly make riprap protection necessary.

* 1976-GPO/1750-S/671-583/72

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